Draft version February 5, 2008
Preprint typeset using LaTeX style emulateapj v. 6/22/04

SPITZER OBSERVATIONS OF CENTAURUS A: INFRARED SYNCHROTRON EMISSION FROM THE NORTHERN LOBE

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Draft version February 5, 2008

ABSTRACT

We present measurements obtained with the *Spitzer Space Telescope* in five bands from 3.6–24 μm of the northern inner radio lobe of Centaurus A, the nearest powerful radio galaxy. We show that this emission is synchrotron in origin. Comparison with ultraviolet observations from *GALEX* shows that diffuse ultraviolet emission exists in a smaller region than the infrared but also coincides with the radio jet. We discuss the possibility, that synchrotron emission is responsible for the ultraviolet emission and conclude that further data are required to confirm this.

Subject headings: galaxies: active, individual(Centaurus A) — radio continuum: galaxies — radiation mechanisms: non-thermal

1. INTRODUCTION

The radio source Centaurus A and its host galaxy, NGC 5128, provide a rare opportunity to observe the detailed behaviour of a recently merged system supporting a powerful active nucleus with jets and extended radio emission. At a distance of 3.4 Mpc (Israel 1998), such that $1'' = 16.5$ pc, Centaurus A is the nearest powerful radio galaxy, and its activity, merger remnants, and starformation may be resolved and studied in detail .

The host galaxy is believed to be a giant elliptical galaxy that recently merged ($\sim$200 Myrs ago) with a small spiral galaxy, producing the prominent dust lanes seen in optical images (Baade & Minkowski 1954; Quillen et al. 1993). The active nucleus gives rise to a jet and counter-jet in the inner arcminute ($1' \approx 1$ kpc) about the nucleus (Feigelson et al. 1981; Hardcastle et al. 2003). On larger scales, giant radio lobes extend over $\sim 6^\circ$ on the sky, with inner radio lobes extending about $6'$ to the north-east and south-west. The focus of this *Letter* is the Northern radio 'jet', $\sim$3–4 kpc from the nucleus (see Figure 1). For a comprehensive review of Centaurus A see, for example, Israel (1998), Morganti et al. (1999) and Junkes et al. (1993).

While jet/lobe emission is broadly understood in terms of synchrotron emission from electrons accelerated in the nuclear jet or in associated shocks, there remain uncertainties when interpreting the details of observed emission. Observing the synchrotron spectrum, particularly at sufficiently high frequencies that the cut-off due to spectral aging is measured, allows the study of the energy distribution of the underlying electron population.

Since the radio emission is produced by long-lived electrons, it alone does not provide detailed information about the underlying physical structure of the emitting plasma. At sites of acceleration, highly energetic electrons may emit at frequencies as high as X-rays (Smith et al. 1983; Feigelson et al. 1981), so a multi-frequency approach is required to study these regions. Infrared (IR) observations provide important constraints at intermediate frequencies in modelling targets.

The *Spitzer Space Telescope* (Werner et al. 2004) offers a powerful new capability to study IR emission from jets in AGN. The Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Imaging Photometer (MIPS; Rieke et al. 2004) provide imaging at 3.6 to 160 μm, with sensitivity orders of magnitude better than any other telescope. Whilst near-IR detections of FRII sources have been made recently (e.g. Floyd et al. 2006), no jet to date has been observed extensively in the IR.

The *Spitzer Space Telescope*'s advantage, in addition to offering several IR bands, is its sensitivity. In this *Letter* we present IRAC and MIPS photometry of the northern radio lobe, based upon effective integrations of 72 s and 160 s respectively, and use them to describe and interpret the jet SED of Centaurus A. The IRAC observations and general processing are described in Quillen et al. (2006). The MIPS data are presented here for the first time. We use radio data at 843 MHz, 1.4 GHz, and 4.9 GHz from the literature: the 843 MHz data are taken from the Sydney University Molonglo Sky Survey (SUMSS; Bock et al. 1999); the 1.4 GHz and 4.9 GHz data are from Condon et al. (1996) and Burns et al. (1983), respectively. We show that the diffuse IR emission is also synchrotron in origin, and compare it to ultraviolet (UV) emission detected by the *Galaxy Evolution Explorer* (*GALEX*; Martin et al. 2005). § 2 presents the MIPS imaging and describes the IRAC, UV, and radio data sets. § 3 describes the method for measuring the surface brightness of the jet and presents the derived photometry. § 4 interprets the results in terms of an underlying synchrotron spectrum and discusses the physical implications.

2. OBSERVATIONS

The multi-wavelength emission we describe (Figure 1) coincides with the part of the jet/lobe system usually referred to as the northern inner radio lobe (NIRL). The NIRL lies between the inner jet and the 'large-scale jet-like feature' which connects the NIRL to the middle radio lobe (Morganti et al. 1999). Centaurus A is a Fanaroff-Riley class I (FR I; Fanaroff & Riley 1974) radio source,

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and has neither the hotspots nor the clear distinction between jet and lobe that characterize FR II sources. Referring to a part of the jet in Centaurus A as a "lobe", therefore, can be confusing, particularly in the context of this *Letter* which discusses its relation to the nucleus. We instead use the term "jet" to describe the source. Figure 1 shows the MIPS 24 μm image overlaid with 1.4 GHz radio contours and should clarify the source position with respect to the literature.

2.1. *MIPS imaging*

Centaurus A was observed with MIPS on 2004 August 6 using scan mapping mode with 14 scan legs at a medium scan rate, resulting in a total exposure of $\sim$160 s at the center of the map. MIPS has three bands centered at 24, 70 and 160 μm with bandwidths of 4.7, 19 and 35 μm, respectively. Due to the presence of the bright, extended, dusty disk, measuring the surface brightness of the jet has only been possible at 24 μm and we present only that data here. The 24 μm band "jail bar" artifacts were corrected by dividing each Basic Calibration Data (BCD) frame by a normalized median frame (based on all BCDs excluding the source). These corrected BCDs were then mosaiced using the MOPEX software using single, multi-frame, and dual outlier rejection (http://ssc.spitzer.caltech.edu/postbcd/). The final mosaiced image is $\sim 21' \times 56'$ and reaches a sensitivity of 0.038 MJy sr^{-1}, with a pixel scale of 2.″5; the resolution is $\sim$6″ (FWHM). Figure 1 (far right) shows a 15.′2 × 10.′5 section centred on the galaxy. The contours describe the 1.4 GHz radio emission of the inner radio lobes, and show that the the jet is clearly detected at 24 μm. The counter-jet/southern radio lobe is not detected.

2.2. *Data at other wavelengths*

IRAC observations at 3.6, 4.5, 5.8, and 8 μm are taken from Quillen et al. (2006) and the 3.6 μm and 8 μm images are shown in Figure 1 (left and middle panels), stretched to emphasize detection of IR emission coincident with the radio lobe. These mosaiced observations had a typical exposure time of 72 s at the source, and reached depths of 0.025, 0.024, 0.07 and 0.06 MJy sr^{-1} in bands 1–4, respectively. Radio data at 1.4 GHz from Condon et al. (1996) show the jet with good signal-to-noise ratio, as do 843 MHz data taken from SUMSS (Bock et al. 1999). In addition, a re-reduced version of the 4.9 GHz data (Burns et al. 1983) was provided by M. Hardcastle (priv. comm.) and used to put limits on the radio emission at that frequency. Ultraviolet observations obtained with *GALEX* (Neff et al. 2003, Neff et al. in prep.) at near and far UV bands cover 1350–1800Å and 1800–2800Å. The effective wavelengths for the bands are 1528 and 2271Årespectively.

3. SURFACE BRIGHTNESS MEASUREMENTS OF THE NORTHERN INNER RADIO LOBE

Measuring the surface brightness of the jet requires careful subtraction of the underlying emission from the host galaxy. This was done by creating an irregularly shaped aperture matched to the jet, and rotating it about the center of the galaxy (i.e., the unresolved nucleus in the 4.5 μm image). The surface brightnesses measured when the aperture was adjacent to the lobe are used to estimate the background due to the galaxy. The aperture is a polygon chosen by eye to match the shape of the lobe in the near UV *GALEX* image[4]. It covers 653 pixels in the IRAC images (1.″22/pixel) and has six points starting at 13 26 24.69 -43 10 16.4 (J2000), with vertices offset by 1.78, 2.47, 1.64, 0.13 and -1.92 s East and 13.5, 30.0, 37.5, 33.0 and 19.5″ North, respectively. Figure 1 (middle) shows the position of the jet aperture overlaid on the 8 μm IRAC image. The aperture was rotated about the center of the galaxy in 100 steps covering $\pi/2$ radians on either side of the jet. At each position, the counts in the aperture were summed, excluding pixels on or near stars or other discrete sources. The mean count per aperture was then plotted as a function of angular separation from the radio lobe. By excluding the region corresponding to the radio lobe and fitting the mean count from apertures on either side of the lobe, an estimate of the background at the lobe was made and subtracted. Linear and quadratic fits to the galaxy background were made. Figure 2 (left) illustrates the 3.6 μm measurement. An estimate of the photometric error was taken to be the standard deviation of the difference between the fit to the background and the measured background across the range of the fit. This typically indicated a 10σ detection and shows that this measurement error dominates the 5% photometric error which is typical of IRAC mosaics. This method was repeated in all four IRAC images, the MIPS 24 μm image, the *GALEX* images, and the radio images.

4. RESULTS AND DISCUSSION

Figure 2 (right) shows the surface brightness of the designated region of the jet of Centaurus A as a function of frequency. The solid line is a power law, $S \propto \nu^{-\alpha}$, fit to the IR points for which $\alpha = 0.68$. This line comes remarkably close to the radio points suggesting that the IR emission is also synchrotron in origin, though the radio points are slightly flatter than the IR points. This suggests the possibility of a break in a synchrotron spectrum, rather than a simple, single power-law spectrum. However this is not a strong conclusion. We conclude that the IR emission is due to synchrotron emission and, when a single power-law is fitted to both the radio and IR points, $\alpha = 0.72$ (the dashed line in Figure 2).

Synchrotron emitting electrons radiate at a rate proportional to their energy. The most energetic electrons lose their energy the fastest, leading to a slope that is one-half power steeper in the high frequency spectrum, at frequencies much above the break frequency, $\nu_B = eB/2\pi m_e c$ (e.g. Beams and Jets in Astrophysics, ed. Hughes, 1991). Our observations indicate that this break must occur at frequencies higher than 10^{13} Hz. Though detailed modelling is required for an exact evaluation of the break frequency, an approximate limit may be gained. Following Miley (1980), we calculate the magnitude of the magnetic field on the assumption that the system is at its minimum energy density. Using Equation 3 of Miley (1980) at 1.4 GHz, we find $B \approx 3$ nT. Using the highest IR frequency observed (83 THz), an

[4] As discussed in § 4, diffuse emission associated with the lobe in the near UV image covers a smaller area than the IR and radio emission in the region. The aperture is therefore based upon the UV data in order that the comparison of the mean surface brightness be fair.

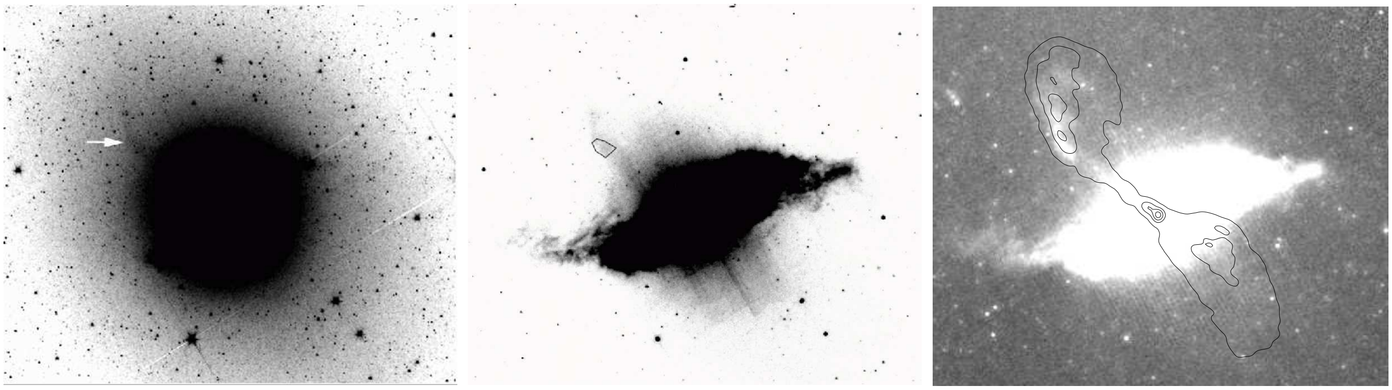

FIG. 1.— Left to right: 3.6 μm IRAC image, 8 μm IRAC image and 24 μm MIPS image. These images show a $15'.2 \times 10'.5$ portion of the final mosaics. They are centred on 13 25 27.5 -43 1 8.5 (J2000), with North towards the top of the page and East to the left. All are stretched to highlight the jet and show the increasing strength of emission towards longer wavelengths. The IRAC images show the aperture used to measure the surface brightness, and the contours on the 24 μm MIPS image describe the 1.4 GHz emission and show how the IR emission coincides with the radio jet.

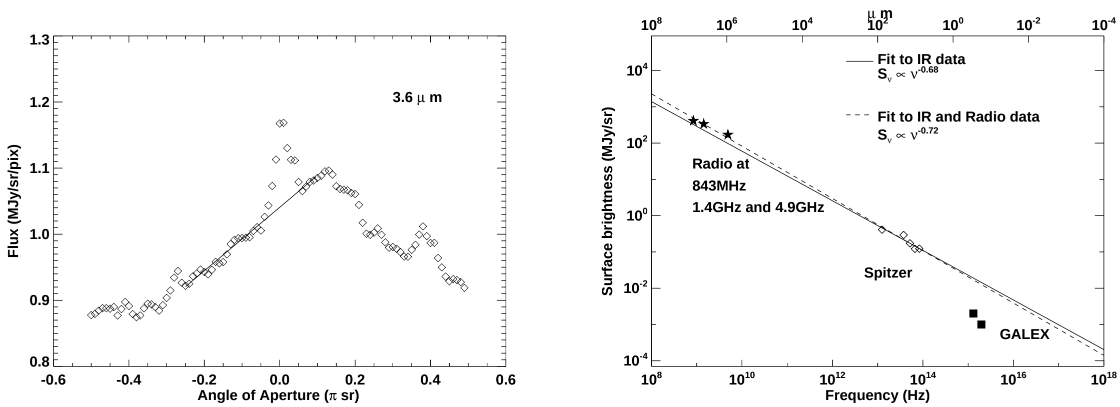

FIG. 2.— Left: Mean counts per aperture as a function of angular position about the nucleus. The abscissa zero point corresponds to the original aperture, chosen by eye to fit the jet shape. The jet surface brightness is determined by subtracting an estimate of the background (fitted to surrounding apertures and shown by the solid line) from the total surface brightness. Right: The spectral energy distribution of the jet of Centaurus A. The surface brightness was determined from a six-points aperture, as described in the text. Errors on the photometry are smaller than the plotting symbols used.

upper limit to the lifetime of the emitting electrons is found to be 30,000 yrs.

It is important to know how far the synchrotron spectrum extends without a break, since very high frequency emission is produced by short-lived, high energy particles and may imply in situ particle acceleration. In both the near UV and far UV *GALEX* images there are two kinds of emission: extended sources, likely associated with star-formation sites; and diffuse emission which coincides with the jet. Figure 3 shows the 1.4 GHz radio contours overlaid on the 8 μm IRAC image in greyscale (left) and the near UV *GALEX* image (right; smoothed with a $7''.6$ circular Gaussian for clarity). The UV emission is seen only at the inner portion of the jet, whereas the IR emission follows the jet to the north, consistent with the idea that emission at all three wavelengths is synchrotron emission. The synchrotron lifetime of the UV emitting electrons is shorter than that of the IR emitting electrons, and so they do not live/emit long enough to trace the bulk motion downstream. northward at this point, indicative of interactions with the environment in the region.

The surface brightness of the diffuse UV emission is compared to that of the radio and IR emission in Figure 2 (right). The UV points are significantly below the extrapolation of the synchrotron emission based upon the radio and IR data. Several explanations must be considered. Firstly, the diffuse UV emission might not be synchrotron at all. We consider this unlikely because the jet emission extends to X-ray frequencies (Kraft et al. 2003), though it is possible that other mechanisms, such as diffuse star-formation, also contribute to the UV. Secondly, we could be seeing the effects of extinction due to dust. Suppose that the best-fit power law to the radio and infrared measurements extends without break to ultraviolet frequencies, but that there is intervening dust. Assuming a Calzetti extinction law, only $E(B-V) = 0.56$ is required to produce the observed ultraviolet emission. Given the violent dynamic history of Centaurus A there is clearly a large presence of gas, and therefore dust, associated with the merger, which can be found in distinct regions far outside the galactic disk. Hence it is plausible that sufficient extinction, at the shortest wavelengths, exists along specific lines of sight. Note that if this were the case, the appropriate synchrotron lifetime for the UV emitting particles ($\sim$ 6000 years) would be short enough to require *in*

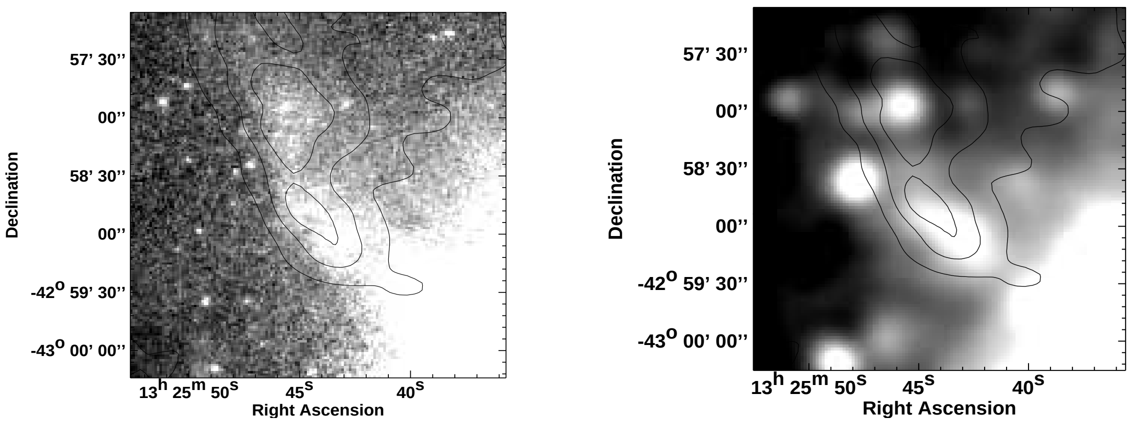

FIG. 3.— Left: 8 μm IRAC image of the jet with contours describing the 1.4 GHz radio emission. Right: Near UV *GALEX* image (smoothed by a 7.″6 circular Gaussian) with 1.4 GHz radio contours. The two sources to the North and East are discrete and are likely to be associated with star-formation sites. Both images show the region of the aperture used to measure the surface brightness (Figure 1).

situ particle acceleration, given a projected distance of $\sim$3 kpc from the nucleus, and bulk motion $\sim$0.5 c in the kpc scale jet (Hardcastle et al. 2003).

However, inclusion of X-ray measurements argues for a third possibility: a spectral break between infrared and ultraviolet frequencies. Hardcastle et al. (2006; henceforth H06) fit a broken power-law spectrum to all measurements from radio to X-ray frequencies, and determine that a break occurs at $\sim$0.3 THz. Figure 5 of H06 shows that this broken power law accounts well for the radio, infrared, and X-ray measurements. However, it significantly underpredicts the ultraviolet measurements, even assuming no extinction from dust intrinsic to Centaurus A (Galactic extinction was included). If intrinsic extinction is important this discrepancy becomes worse.

Neither dust alone, nor a broken power-law accounts for the data in an entirely satisfactory way. Submillimeter and 70 μm *Spitzer* measurements with higher SNR would fill in the gap in the observed spectrum above and below 1 THz, providing significant new constraints on the overall spectrum, and would help in resolving the issue.

5. SUMMARY

New IR observations of the jet, at the position of the NIRL associated with Centaurus A obtained with the *Spitzer Space Telescope* show that synchrotron emission extends at least from radio to IR wavelengths. Diffuse UV emission is also present in the jet and it is plausible that this emission is also synchrotron in origin, reddened by intervening dust. X-ray data imply a break in the spectrum, but further data are required to constrain this precisely.

This work is based on observations with the NASA *Spitzer Space Telescope*, which is operated by the California Institute of Technology for NASA under NASA contract 1407. We wish to thank Susan Neff from the *GALEX* team for providing the UV data and her useful discussions. We also thank Martin Hardcastle for providing the re-reduced 4.9 GHz radio data and his part in coordinating the publication of these results.

REFERENCES

Baade, W., Minkowski, R., 1954, ApJ, 119, 215
Bock, D.C.-J., Large, M.I., Sadler, E.M., 1999, AJ, 117, 1578
Burns, J.O., Feigelson, E.D., Schreier, E.J., 1983, ApJ, 273, 128
Charmandaris, V., Combes, F., van der Hulst, J.M., 2000, A&A, 356, 1
Condon, J.J., Helou, G., Sanders, B.D., Soifer, B.T., 1996, ApJS, 103, 81
Eckart, A., et al., 1990, ApJ, 363, 451
Fanaroff, B.L., Riley, J.M., 1974, MNRAS, 167, 31
Fazio, G.G., et al., 2004, ApJS, 154, 10
Feigelson, E.D., Schreier, E.J., Delvaille, J.P., Giaconni, R., Grindlay, J.E., Lightman, A.P., 1981, ApJ, 251, 31
Floyd, D.J.E. et al. 2006, ApJ, astro-ph/0602021
Hardcastle, M.J., Worrall, D.M., Kraft, R.P., Forman, W.R., Jones, C., Murray, S.S., 2003, ApJ, 593, 169
Hardcastle, M.J., Kraft, R.P., Worrall, D.M., 2006, MNRAS, 368, 15
Hughes, P.A.(ed.), Beams and Jets in Astrophysics, 1991 (Cambridge: CUP)
Israel, F.P., 1998, A&A Rev., 8, 237
Jones, P.A., McAdam, W.B., 1992, ApJS, 80, 137
Junkes, N., Haynes, R.F., Harnett, J.I., Jauncey, D.L., 1993, A&A, 269, 29
Karovska, M., Fabbiano, G., Nicastro, F., Elvis, M., Kraft, R.P., Murray, S.S., 2002, ApJ, 577, 114
Kormendy, J., Gebhardt, K., 2002, 20th Texas Symp. on Relativistic Astrophysics, ed. Martel & Wheeler, AIP
Kraft, R.P., Vázquez, S.E., Forman, W.R., Jones, C., Murray, S.S., Hardcastle, M.J., Worrall, D.M., Churazov, E., 2003, ApJ, 592, 129
Martin, D.C., et al., 2005, ApJ, 619, 1
Morganti, R., Killeen, N.E.B., Ekers, R.D., Oosterloo, T.A., 1999, MNRAS, 307, 750
Miley, G., 1980, ARA&A, 18, 165
Neff, S.G., Schiminovich, D., Martin, C.D., *GALEX* Science Team, 2003, American Astronomical Society Meeting Abstracts, 203, 9607
Perlman, E.S., Sparks, W.B., Radomski, J., Packham, C., Fisher, R.S., Piña, R., Biretta, J.A., 2001, ApJ, 561, 51
Rieke, G.H., et al., 2004, ApJS, 154, 25
Smith, R.M., Bicknell, G.V., Hyland, A.R., Jones, T.J., 1983, ApJ, 266, 69

Springel, V., Di Matteo, T., Hernquist, L., 2005, MNRAS, 361, 776
Quillen,A.C., Graham, J.R., Frogel, J.A., 1993, ApJ, 412, 550
Quillen A.C. et al., 2006, submitted to ApJ, astro-ph/0601135
Uchiyama, Y., Urry, C.M., Van Duyne, J.,Cheung, C.C., Sambruna, R.M., Takashi, T., Tavecchio, F., Maraschi, L., 2005, ApJ, 621, 113
Werner M.W. et al., 2004, ApJS, 154, 1